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Reduction of methane emission from landfills using bio-mitigation systems – from lab tests to full scale implementation

***Peter Kjeldsen*[1] *and Charlotte Scheutz*[2]**

Abstract

Landfills are significant sources of methane, which contributes to climate change. As an alternative to mitigation by gas utilization systems, bio-mitigation systems may be implemented. Such systems are based on microbial methane oxidation in full surface biological covers, so-called biocovers, or open or closed bed biofilter systems. The objective of this paper is to describe the relationship between research on process understanding of the oxidation of landfill gas contained methane and the up-scale to full bio-mitigation systems implemented at landfills. The oxidation of methane is controlled by several environmental factors such as soil texture, temperature, soil moisture content, methane and oxygen supply, and nutrients, and both soils and compost materials have been shown to exhibit high methane oxidation rates. For compost materials high methane oxidation is observed even during cold periods due to self-heating processes. Bio-mitigation can be used as a stand-alone technology or combined with active or passive gas collection. When implementing bio-mitigation systems focus should be on additional fugitive methane emissions or the presence of uncontrolled point releases. A protocol for implementing a bio-mitigation system is presented, and the reported landfill-implemented bio-mitigation systems either established as full-scale or pilot-scale systems are reviewed. It is concluded that bio-mitigation systems have a large potential for providing cost-efficient mitigation options for reducing methane emissions when landfill gas utilization systems cannot be implemented or cease to perform as cost-efficient, sustainable solutions.

Keywords: Biocover, Biofiltration, Climate change, Landfill gas management, Methane oxidation, Waste Disposal

1. INTRODUCTION

Landfills receiving organic wastes produce biogas containing methane (CH_4). Landfills are significant sources of CH_4, which contributes to climate change [1]. At some landfills utilization of landfill gas (LFG) is not or cannot be carried out, and the gas is either flared with risk of producing toxic combustion products or just emitted to atmosphere. As an alternative to gas utilization systems or as a follow-on technology when a gas utilization system gets non-cost-effective, bio-mitigation systems may be implemented [2]. Bio-mitigation systems are defined here as systems based on microbial removal processes implemented at landfills to reduce emission of methane (or other harmful substances). In respect to CH_4, experiments have documented that a very high CH_4 oxidation rate can be obtained in soils, compost and other materials, high enough to significant reduce the CH_4 emission from landfills [3]. Landfills may be fully covered with biological active materials, so-called biocovers. Bio-mitigation systems may also imply establishment of biofilters reducing CH_4 concentration in LFG extracted from the existing gas collection system (GCS).

The objective of this paper is to describe the relationship between research on process understanding of the oxidation of LFG contained CH_4 and the up-scale to full bio-mitigation systems implemented at landfills. The paper describes the different types of bio-mitigation systems, reviews the reported bio-mitigation system implementation described in the literature, and highlights the existing challenges for obtaining systems with high mitigation efficiencies.

2. FROM PROCESS UNDERSTANDING TO TECHNOLOGY DEVELOPMENT

Developing cost-efficient and sustainable environmental technologies is based on a detailed understanding of the governing physical, chemical and microbial processes. This is also truly the case for engineering the microbial CH_4 oxidation process to viable bio-mitigation solutions. The research into the CH_4 oxidation process in landfill covers and surroundings started nearly 25 years ago with the highly-cited paper by Whalen and coworkers [4]. Now (January 2014) with a topical search in Web of Science combining “landfill” and “methane oxidation” 333 articles are found. In the early years most research focused on characterization of the methanotrophic bacteria, laboratory experiments to determine CH_4 oxidation rates and governing environmental factors, field studies of the CH_4 oxidation in

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landfill soil covers and development of simple models to simulate the dynamic behavior of CH_4 in soils. Lately (typical starting around 2005) there has been more focus on engineering the CH_4 oxidation process by implementing bio-mitigation technologies, and also on the use of alternative materials than soils (such as matured compost, clay pellets and other artificial materials).

2.1. The methane oxidation process as basis for bio-mitigation – what is important?

The aerobic microbial oxidation of CH_4 occurs in the biosphere wherever CH_4 and oxygen (O_2) are present at the same location. In landfill covers CH_4 and O_2 may appear at the same depth due to emission of CH_4 from the waste and diffusion of O_2 from ambient air, which provides needed conditions for the development of methanotrophic bacteria [3]. Aerobic CH_4 oxidation proceeds according to the following overall reaction, producing a significant amount of heat:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O + \text{heat} \qquad \Delta G° = -780\text{kJ/mol } CH_4 \qquad (1)$$

The reaction is carried out by the so-called methanotrophic bacteria (or methanotrophs), which are unique in their ability to utilize CH_4 as a carbon and energy source [3]. Landfill cover soils can exhibit high capacities for CH_4 oxidation. Very high rates of CH_4 oxidation in landfill cover soils (>100 µg CH_4 g^{-1} h^{-1} and >200 g CH_4 m^{-2} d^{-1} in batch and column experiments, respectively) have been reported [3].

The oxidation of CH_4 is controlled by several environmental factors such as soil texture, temperature, soil moisture content, CH_4 and O_2 supply, nutrients, etc. This implies that the climatic conditions are of huge importance for the actual CH_4 oxidation rate. In landfill soil covers or engineered bio-mitigation systems, temperature and soil moisture are very important parameters controlling CH_4 oxidation [3]. Especially temperature is an important factor in temperate and arctic climate where ambient temperature can be limiting for the biological process during the winter season. However, several later studies of bio-mitigation systems using compost as bio-active material have shown significant elevated temperatures in the CH_4 oxidation layer during cold periods ([5]-[9]), which affect the biocover ability to oxidize CH_4 in a positive direction. This is supported by laboratory experiments, which investigated the influence of the temperature on CH_4 oxidation and respiration in compost samples [10]. Compost material was collected from the bio-mitigation system at Klintholm landfill and incubated in the laboratory at ten different temperatures varying between 4 ºC and 70 ºC. The temperature optimum of the methanotrophic community in the biocover material was 45 °C (see Figure 1), which was much higher than the temperature optimum for CH_4 oxidation in landfill cover soils, which has been reported to be in the range of 15 to 38 °C [3]. The results indicate that a moderately thermophilic methanotrophic community adapted to the elevated temperature conditions in the biocover had developed. The temperature optimum was comparable to maximum temperatures measured in the deeper parts of the biocover at Klintholm Landfill [10].

Moisture content may also be an important environmental factor. LFG flowing through the CH_4 oxidation layer (MOL) may be heated up due to the elevated temperatures (as described above) and evaporate water contained in the MOL. Even though that the CH_4 oxidation process produces water (confer equation 1) and that the LFG often is water saturated when leaving the waste layers, a desiccation of the MOL may be observed especially in hot, dry region with little infiltration of rain.

2.2. The role of bio-mitigation systems in landfill gas management

Landfills are still the dominant option for waste disposal in many parts of the world. In many countries (including USA, Australia, Greece, UK) between 50 and 80% of municipal solid waste generated is still landfilled [11]. There are still a high number of active landfills in these countries, and also a high number has been closed within the last 10-15 years. Besides, still a large number of old, uncontrolled landfills still exists in all countries producing significant volumes of LFG. In the western countries many landfills have been equipped with GCSs with energy utilization or alternatively with flaring.

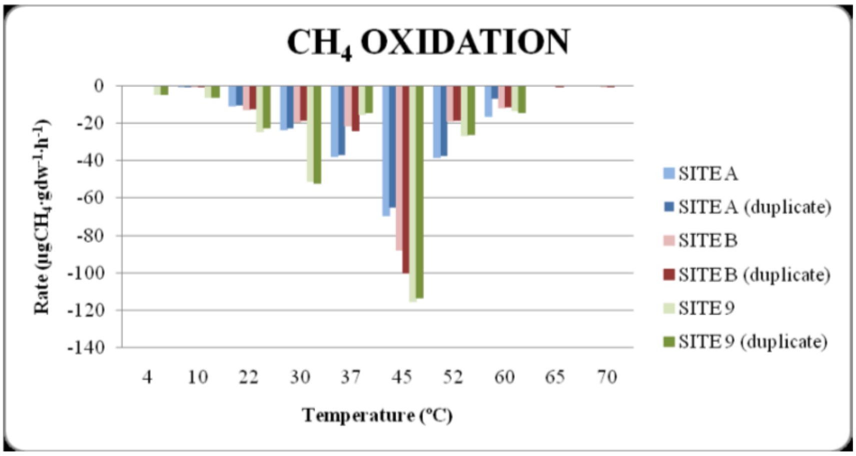

Figure 1. CH_4 oxidation rates as a function of temperature obtained from CH_4 oxidation tests with compost materials sampled at three locations at the biocover at Klintholm landfill, [10].

Table 1. Scenarios where establishment of a bio-mitigation system at landfills could be an option.

Scenario	Description
1	No gas collection system (GCS) is in place, the LFG generation is modest either due to a high landfill age or disposal of waste with low organic content. Installation of a GCS and a gas engine (or similar energy conversion unit) is not cost-efficient, but LFG emission is regarded as above legal limits. 1a. No leachate collection system is present nor gas vents, which could be the major LFG escaping route 1b. A leachate collection system or gas vents are present, which may be the major LFG escaping route
2	A GCS is in place. The gas engine (or similar energy conversion unit) is old with high running maintenance costs. A replacement of the energy conversion unit is considered non-cost-efficient. 2a. Significant fugitive or un-collected emissions from slopes, uncovered part, leachate collection system, etc. are foreseen 2b. No significant fugitive emissions are foreseen - may be as a result of the presence of a gas tight engineered top cover
3	A GCS and a gas flaring system are in place. The flares have difficulties to run without the use of supporting fuel, but LFG emission is regarded as above legal limits. 3a. Significant fugitive or un-collected emissions from slopes, uncovered part, leachate collection system, etc. are foreseen 3b. No significant fugitive emissions are foreseen - may be as a result of the presence of a gas tight engineered top cover

However, in general on a global scale, the major fraction of new as well as old landfills are not equipped with gas management systems, perhaps except installed gas vents to avoid of-site migration and reduce explosion hazards. The gas vents are releasing the LFG directly to the atmosphere being a severe CH_4 source contributing to the greenhouse effect.

The establishment of a bio-mitigation system may be relevant in several different cases. However, it is important to stress that LFG extraction and energy utilization often will be highly cost-efficient at large, newer landfills. Besides the mitigation effect by reducing emissions of CH_4, the energy production indirectly also saves CO_2 emissions (in case that the LFG based energy replaces energy produced from fossil fuels). At high gas generation rates, bio-mitigation systems are also of minor relevance due to the foreseen high gas loads to the system, which may give inadequate retention times in the bio-filtration units and a resulting low mitigation efficiency of the system.

Table 1 gives an overview on the different scenarios where a bio-mitigation system may be implemented. The different scenarios may lead to the establishment of different bio-mitigation systems depending on the specific, local conditions. In the next section the different types of bio-mitigation systems are described.

2.3. Types of bio-mitigation systems

Table 2 defines the different bio-mitigation systems, which can be used for mitigation of CH_4emissions from landfills. A *full surface biocover* is a landfill cover system that has been designed to optimize environmental conditions for biotic CH_4 consumption, so that the system functions as a vast bio-filter. The cover typically consists of a basal ‘gas distribution layer’ (GDL), with high gas permeability to homogenize LFG fluxes, and an overlying ‘methane oxidation layer’ (MOL), designed to support the methanotrophic populations that will consume the CH_4. Since biocovers are typically spread over an entire landfill area or sector, cost becomes a critical factor in material selection, and often raw or composted waste materials, such as dewatered sewage sludge or yard waste, are used. Another critical factor is the permeability of any interim soil cover below the biocover. If the gas permeability is too low to allow flow of the LFG loading the biocover, hot spot CH_4 releases may occur at points or areas where less tight soil cover materials have been used. A *biowindow system* accommodates the problem of an existing low permeable soil cover by construction of areas where the soil is replaced by a biofilter, so-called biowindows (see Figure 2). This option reduces the areas over which the LFG is escaping, leading to lower gas retention times in the filter material. A biowindow system is therefore most relevant at reduced LFG generation rates and at landfills, which are finally covered with relatively gas impermeable materials For both the biocover and the biowindow, the gas is loaded passively to the filter.

Biofilters, like biocovers, exploit CH_4 oxidizing bacteria to mitigate low calorific landfill CH_4 emissions. Operated as self-contained fixed bed reactors with a packing material to support and sustain a methanotrophic biofilm, biofilters can accomplish high CH_4 removal rates. Unlike biocovers, biofilters require a supply of gas, which is usually provided by a gas collection or drainage system. The supply can be either passive supported by the elevated gas pressure inside the landfill as a result of the gas generation process, or active by use of gas pumps. A biofilter can either be open bed (allowing oxygen diffusion from the atmosphere) or closed bed where the supply gas should contain all relevant gases (both CH_4 and O_2) (see Figure 3). The use of closed bed systems may be constrained by the total gas load. At high gas loads, the total volume of biofilter material needed for the biofilter may give rather costly solutions.

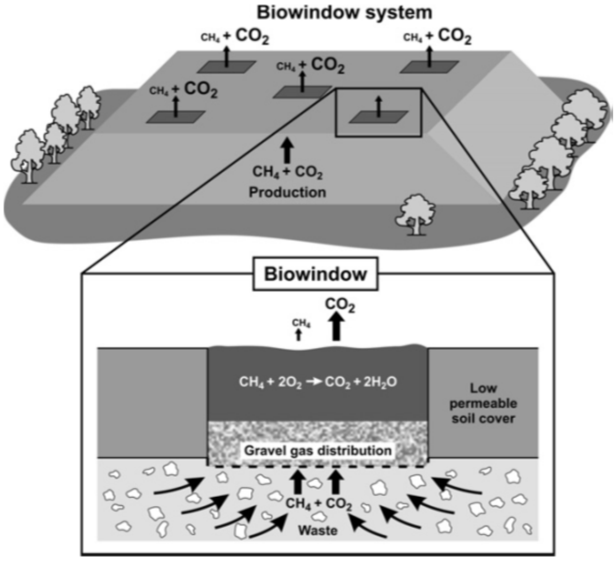

Figure 2. Illustration of the biowindows concept to facilitate biological CH4 oxidation, and thereby reduce greenhouse gas emissions from a landfill [16].

Table 2. Different types of systems for bio-mitigation of CH_4 emissions from landfills.

Type	**Abbrev.**	**Description**
Full surface biocover	FSB	The whole landfill area is covered with a homogenous layer of bioactive coarse materials (such as a coarse soil or compost)
Biowindow system	BWS	A system incorporating the presence of an existing, low permeable soil cover. Areas of the existing cover is replaced by gas permeable, bioactive materials (such as a coarse soil or compost) underlain by a gas distribution layer of gravel. Gas is loaded passively to the biowindows.
Biofilter passive, open bed	BF-PO	A system consisting of a volume of bioactive materials where LFG is fed passively from below through a gas distribution layer. Open to the atmosphere so oxygen can diffuse into the bioactive material from above.
Biofilter passive, closed bed	BF-PC	A system consisting of a volume of bioactive materials where LFG is fed passively from below/above through a gas distribution layer. Closed to the atmosphere (for instance in a container) so oxygen is to be part of the loading gas.
Biofilter active, open bed	BF-AO	A system consisting of a volume of bioactive materials where LFG is actively pumped from below through a gas distribution layer. The biofilter surface is open to the atmosphere so oxygen can diffuse into the bioactive material from above.
Biofilter active, closed bed	BF-AC	A system consisting of a volume of bioactive materials where LFG is actively pumped from below/above through a gas distribution layer. The biofilter is inclosed (for instance in a container) so oxygen is to be part of the loading gas (maybe supplied by a second pump).
Bioactive intercepting trench	BIT-PO	A system consisting of a deep trench surrounding the perimeter of a landfill to collect and oxidize CH_4 in LFG migrating horizontally from the landfill. The trench may be filled with gas distributing materials at the bottom and bioactive materials on top.
Combined solutions	-	A system combining some of the types above, for instance a full surface biocover to reduce fugitive emissions with a biofilter treating LFG collected from a gas extraction system

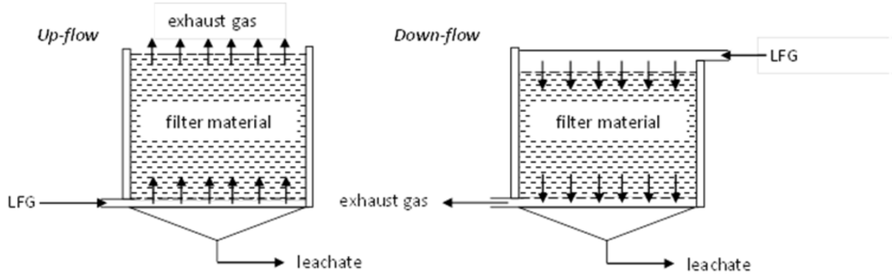

Figure 3. Standard variants of biofilter design showing the open-bed, up-flow and closed-bed, down-flow versions., [3].

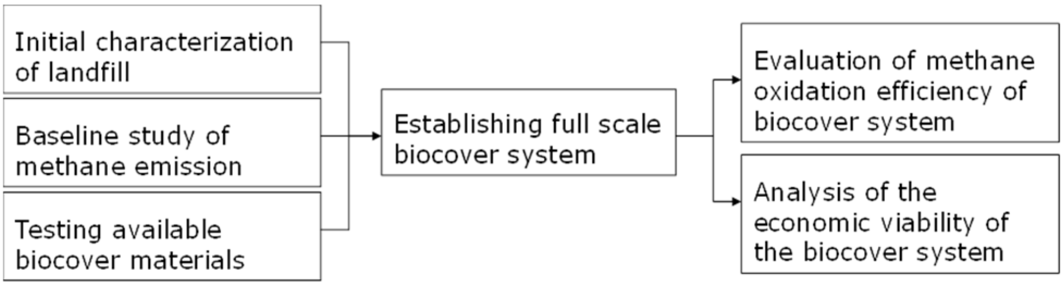

Figure 4. Description of the biocover system approach with the logical order of project activities, [8].

2.4. Protocol for establishing a bio-mitigation systems

Through the work on establishing bio-mitigation systems at Danish landfills a protocol framework for the establishment has been developed. The framework is shown in Figure 4, which presents the different project activities. A few comments are given to each of the project steps in the following section.

Initial characterization of landfill. The objective of this task is to establish the basis for implementation of the project based on existing data (such as landfill area, total waste volume, received waste types, waste masses per year, etc.) combined with site visits and gathering of new basic data concerning the existing soil cover of the landfill. The expected gas generation from the landfill is predicted by use of a LFG generation model using the collected data on waste types, volumes and ages. This task is especially important for a Scenario 1 type project (see Table 2).

Baseline study of methane emission. The objective of this task is to obtain a measurement of the baseline emission of CH_4 from the landfill in tons per year. In order to evaluate the efficiency of an installed bio-mitigation system for CH_4 mitigation, the CH_4 emission after establishing the bio-mitigation system is to be compared with the baseline emission. The total CH_4 emission from the landfill can be determined by performance of a series of campaigns using the tracer dilution method [12]. The task should also evaluate the spatial distribution of fugitive emission from the landfill surface by screening surface CH_4 concentrations using a FID-detector eventually in combination with flux chamber measurements. Also the presence of point CH_4 source releases such as leachate wells, inspection wells, and gas vents should be evaluated and emissions measured (eventually using a small scale version of the tracer dilution method [13]. For scenario 2 and 3 types (Table 2), annual collected CH_4 by the GCS is determined and the significance of un-collected CH_4 (fugitive emitted and point source released) is evaluated.

Testing available bio-active materials. The objective of this task is to identify locally available materials for potential use in the bio-mitigation system, and test the materials and combinations of materials in the laboratory in order to determine the CH_4 oxidation capacity of available materials/combination of materials [14]. The bio-active materials could be compost, which in many cases is produced from garden waste and sludge at the landfill. Compost is often produced in large quantities and it can be difficult to find adequate need for the compost for normal use as soil quality improvement material. The test can be done by batch incubation tests or dynamic column tests simulating the biofiltration process [14].

Establishing the full scale bio-mitigation system. Based on the findings from the three previous tasks the type of bio-mitigation system is chosen (see Table 2 and 3). Activities are made to reduce any fugitive emissions by improving the existing soil cover or to reduce any hot spot CH_4 releases – in case a *full surface biocover* is chosen. For cases where a GCS is in place, un-collected point sources (such as leachate wells) are connected to the GCS and a biofilter solution is chosen and dimensioned based on the measured CH_4 emission plus CH_4 collected, using the CH_4 oxidation capacity determined by the laboratory experiments (as described above) giving the needed filter volume/area.

Table 3. Compilation of established bio-mitigation systems at landfills reported in literature.

Landfill Area (ha)/Waste mass (ktons)/ Type (Table 1)	Country	Scale[a] FS/PS	System type[b]	Typical gas composition[c] (%CH_4/%O_2)	Active material[d] Type/A(m^2)/D(cm)	Gas Distr. layer[e], D(cm)	Total efficiency evaluated?[f] GL($g/m^{-2}d^{-1}$)/ME(%)	Measurement methods used[g]	Efficiency Approach[h]	Certainty in efficiency evaluation (+ → ++++)	Ref.
Aikkala (3.9/200/ 1a)	SF	FS	FSB (with gas wells)	31-72/1-5	C/39,000/50	50	32-216/25-46	FC, PGP	TMMB	++	[15]
Fakse (12/660/ 1b)	DK	FS	BWS	40-65/0	C/5000/100	15	150/28	WLEM, MMS, FC, PGP, SCIC	TEBA, CMB	++	[16]
Klintholm (4/480/ 1a)	DK	FS	BF-PO	69/0	C/4800/80	30	50/80	WLEM, MSS, FC, PGP	TEBA	+++	[8]
Landfill x (n.r./n.r./ 3)	GB	FS	BF-AO	20-40/n.r.	C and CP/4X150/ 130	(30)	530/55-99	MSS, FC, PGP, MF	TMMB, PBE	+++	[17]
Outer Loop	USA	PS	FSB/BWS	n.r.	C and S/n.r./100	0/15	n.d./21-55	FC, SCIC	LMMB	+	[18]
Leon County (n.r./n.r./ 1)	USA	PS	BWS	54-68/n.r.	C/2x580/30 or 60	15	300-700//20-60	FC, SCIC	other	++	[19]
Leduc and District regional	CAN	PS	BWS	n.r./n.r.	C/10 or 20/150	80	40-50/20-90	FC, PGP	CMB	++	[5]
Podere Casa Rota	I	PS	BWS	20-40/<1	C/4x25/70	10	n.d./64-84	FC, PGP	CMB, PBE	+	[20]
Horsley Park	AUS	PS	BIT-PO	49/1.9	C/15/100	250	n.d./>35	FC, PGP	CMB	++	[21]
Kelso (n.r./3000/ 1a)	AUS	PS	BF-PO	45-55/0.5	C/4x9/120	50	8-27/20-70	FC, PGP, MF	CMB	+++	[7],[22]
St-Nicéphore	CAN	PS	BF-PO	n.r./n.r.	C/23/80	30	175/73-99	FC, PGP	TMMB	+	[23]
Landfill y	CAN	PS	BF-PO	n.r./n.r.	C/100/90	30	n.r./n.r.	FC?	?	-	[24]
Hamburg harbor sl.	DE	PS	BF-PO	n.r./n.r.	CP/17/80	20	125-600/>97%	FC, MF	TMMB	++	[25]
AV Miljø (40/2000/ 1b)	DK	PS	BF-AO	7/12	C/500/85	40	12/97	MSS, FC, PGP, MF		+++	[26],[27]
Wieringermeer	NL	PS	BF-AO	n.r./n.r.	S/510/100	20	43/30-96	FC(large), PGP, MF	TMMB, PBE, CMB	+++	[28]
2 French landfills	F	PS	BF-AC	2-2.5/18-20	C/17m^3/n.r	(30)	620/15-17, max 60	MF, FC		+++	[29]

a: FS: Full Scale, PS: Pilot scale
b: See Table 2 for explanation
c: Composition of CH_4 and O_2 in LFG
d: Active Material
Type: S (soil), C(compost matr.), CP(expanded clay pellets), O(other)
A: area in m^2; D: Layer thickness (cm)
e: D: Thickness of Gas Distribution Layer (cm)

f: GL: Reported average gas load to biocover system; ME: Reported methane removal efficiency
g: Methods supporting performance evaluation
WLEM: Whole landfill emission measurement using tracer dilution approach or other method
FC: Flux chamber measurements
PGP: Pore gas profiles
MSS: methane surface screen
SCIC: Stable carbon isotope composition
MF: mass flow (gas flow and CH_4 content)

h: Efficiency approach: CMB: Carbon mass balance ([30]; PBE: profile based efficiency [31]; LMMB: local methane mass balance: TMMB: total methane mass balance;
TEBA: Total CH_4 emission – before and after

Evaluation of methane oxidation efficiency of the bio-mitigation system. The overall objective of this task is to document the CH_4 mitigation efficiency of the establish system. After establishment of the bio-mitigation system, an initial screening of the surface CH_4 emission and the spatial variability is performed on the entire landfill surface by a FID-detector. If areas with high CH_4 emissions are identified during the screening, the cover properties in these areas should be improved to avoid hot spot emissions. The total CH_4 emission from the landfill is determined again (using the method used in the baseline study) and results from the baseline study and the period after the bio-mitigation system has been established is compared and the CH_4 mitigation efficiency is calculated.

Analysis of the economic viability of the biocover technology. The objective of this task is to evaluate the economic viability of the established bio-mitigation system. The annual reduction in emission of CO_2-equivalents is predicted for the following years based on the determined mitigation efficiency. The related costs is calculated including construction costs and running costs (for maintaining the bio-mitigation system), and a normalized price is determined (€/tons CO_2-eq. mitigated).

3. OVERVIEW ON BIO-MITIGATION SYSTEMS ESTABLISHED IN THE FIELD

During the last ten years, establishment of several bio-mitigation systems for reduction of methane emissions at landfills have been reported. The reported systems imply both full scale systems handling the CH_4 emission from a whole landfill (or landfill cell) and pilot scale systems only treating the CH_4 from a part of the landfill (or few landfill cells). Table 3 is a compilation of the reported systems giving details in respect to landfill setting, scale, system type, monitoring methods, mitigation efficiency, etc. In total, 16 projects are reported in the table, where four are full-scale implementations using four different project types (as defined in Table 2). Most of the projects are using compost type materials as bio-active media in the methane oxidation layer. The largest full scale project is carried out at the Finnish landfill, Aikkala, where a *full surface biocover* is implemented on the 3.9 ha landfill surface loaded by horizontal gas distribution pipes connected to several gas wells. The Klintholm project is a full-scale project established on a 4 ha large landfill cell, not equipped with a gas or leachate collection systems. The bio-mitigation project includes ten passively loaded, open bed biofilters with a total area of 4,800 m^2. The Klintholm project is the only project (besides the Fakse project), which base the mitigation efficiency evaluation on the TEMBA approach (<u>T</u>otal <u>E</u>mission <u>M</u>easurement <u>B</u>efore and <u>A</u>fter the system establishment) using the tracer dilution methodology, and has the highest documented efficiency of the reported full-scale systems.

One of the most important challenges of the non-biofilter systems is to determine the gas load to the active biofiltration units, and it can be uncertain to determine the system efficiency is such cases. Often used approaches are the carbon mass balance (CMB) approach first described in [30] and the profile based efficiency (PBE) approach described in [31].

Many of the pilot scale projects are based on either passively or actively loaded open bed biofilters with filter sizes from 10 m^2 up to over 500 m^2. The gas loading rates reported vary a lot from 8 g CH_4/(m^2 and day) up to more than 700 CH_4/(m^2 and day) and there seems not to be a clear correlation on gas loading rate to mitigation efficiency. It is clear that there is still a lot to learn on the most important environmental factors governing the efficiency of biofiltration.

Two of the projects differ from the others; the Horsley Park project is of the type "Interception trench", with the main aim of reducing of-site gas migration without introducing an additional CH_4 source by traditional soil gas venting using high pumping rates in installed pump wells. Another project is the last presented in Table 3, which is a closed bed biofilter project carried out at two French landfills. The biofilters are treating very diluted LFG (CH_4 content of 2-2.5% (vol.)) but still with high loading rates resulting in relatively low mitigation efficiencies. The efficiencies were constrained by low temperatures during winter, and desiccation leading to by-passing gas flow in the biofilter material.

4. CHALLENGES IN BIO-MITIGATION SYSTEMS AND FUTURE RESEARCH NEEDS

The experiences with research and demonstration activities in relation to bio-mitigation of LFG emissions have shown that there exist potential effective technologies, which may be implemented in full-scale to reduce CH_4 emissions from landfills depending on the existing LFG management. The use of compost based materials seems to be of advantage especially in regions with cold climate during winter time. In many projects elevated temperatures to ambient temperatures have been observed in the methane oxidation layer due to a self-heating process, which has resulted in high oxidation rates even during cold periods. Projects have, however, also shown that the compost is further decomposed over time due to the on-going respiration process, and longevity issues may arise due to decreasing compost permeability and diffusivity potentially deteriorating the functionality of the biofilter units.

Another challenge, which has been observed in many projects is to obtain an even distribution of gas load to the biofilter unit whenever it is part of a full surface biocover, a biowindow system or a biofilter-based system. Research is needed to evaluate different gas distribution systems and to identify the systems, which gives the most cost-efficient solution to the gas distribution issue. For open bed systems (including full surface biocovers and biowindows) another challenge is to manage the water infiltration, which will take place as a result of precipitation. There are reports on problems with water saturated layers blocking the vertical gas transport maybe due to capillary effects in the interface between the methane oxidation layer and the gas distribution layer. In the AV Miljø project ([26],[27]) a system was implemented to reduce such capillary effect, which seemed to work. However, more research is needed to avoid capillary effects.

The physical, chemical and microbial processes, which govern the efficiency of a bio-mitigation system, are highly inter-connected and there is a need for developing advanced mathematical model for predicting and simulating the performance of bio-mitigation systems to be able to fine-tune the systems for obtaining a higher mitigation efficiency of the systems.

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